Optimization of parameters of abdominal muscles stimulation for augmentation of pulmonary ventilation in tetraplegia

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Abstract—
The effects of variations of different parameters of functional electrical stimulation (FES) and abdominal muscles stimulated on pulmonary ventilation were tested in a group of 5 spinal cord injury (SCI) patients and 6 neurologicaly intact subjects. The results showed significantly increased tidal volume and total ventilation in normal subjects and SCI patients during FES. Prolongation of stimulus increased V_T and decreased breathing rate, total ventilation being unchanged. At the same parameters of FES of different combinations of muscles groups, no significant differences in pulmonary ventilation were observed in both groups. Rectus abdominis muscles stimulation with duration of stimulation sequence of one second would be the most convenient choice for the starting phase of FES supported ventilation. In each patient, by further adjustments of FES duration, mode (possibly intermittent) and stimulated muscles groups, demanded ventilatory effects can be achieved. Further investigations have to be performed to take these conclusions as clinically applicable.

Index Terms
Functional electrical stimulation (FES), SCI patients, pulmonary ventilation, abdominal muscles

I. Introduction

The important causes of death in individuals with SCI are diseases of the respiratory system [1]. It is well documented that individuals with SCI, particularly the higher level injuries, have impaired ventilation. They must often limit their activity, are highly susceptible to fatigue, and have an increased level of medical complications which are primarily respiratory related. Important goal of medical support and/or rehabilitation procedure is to strengthen respiratory muscles to sustain adequate ventilation according to metabolic demands of the patients. In the cases of noninvasive support insufficiency, mechanical ventilation is the treatment of choice.

Experimental results of functional electrical stimulation (FES) of abdominal muscles in normal subjects [2], promise a new option of ventilatory support with active participation of patient's respiratory muscles. Tidal volume can be significantly increased by applying electrical stimulation to the abdominal muscles in synchrony with naturally occurring expiration. Important patient's participation is muscular force of expiratory muscles - abdominal muscles.

The new method used in this study has the potential to become an additional technique in pulmonary rehabilitation and support of activity of daily living (ADL).

Muscular fatigue is potential limiting factor. To avoid this the minimal parameters of stimulation to achieve maximal ventilatory effects has to be determined.

The aim of this study was the attempt to find out optimal FES parameters of abdominal muscles to augment pulmonary ventilation in SCI patients.

II. Subjects and Methods

In experiment we tested a group of 5 SCI patients (level of injury C4 - C7, time after injury over 10 years) and 6 neurologicaly intact subjects (M/F 2/4) as a control group. All subjects were without pulmonary complaints, in control group pulmonary function tests were within normal range. In SCI patients restrictive ventilatory pattern was present. Forced vital capacity and forced expiratory volume in first second were lowered for about 50% of reference values.

Commercially available neuromuscular stimulation electrodes (3x8 cm rectangle, PALS, Axelgaard Mfg.) were placed on abdomen symmetrically along the mid-line. For rectus abdominis muscles stimulation, the upper electrodes were positioned just under the costal margin and the lower ones above symphysis bone. For lateral abdominal muscles stimulation electrodes were placed in lumbar region and in parallel besides to rectus muscles.

Stimulation was performed with custom made four-channel electrical stimulator with following characteristics: stimulator is microprocessor controlled, has a/d converter and is monitored with the analogue signal from an airflow sensor (sampled: 10 samples per second). Threshold of stimulation was determined with

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15% of peak expiratory flow obtained during quiet breathing. We used following parameters of stimulation:

- duration of stimulation: 1 sec.,1.5 sec., 2 sec.,
- pulse width linear increase: from 25 µs to 350 µs
- stimulation pulse frequency: 50 Hz.

Flows were measured with pneumotachograph.

Protocol:

- supine position
- Muscles stimulated rectus abdominis, lateral abdominal group of muscles (mm. transversi, mm obliqui externi et interni), and both groups.
- duration of stimulus: 1 s, 1.5 s, 2 s.
- the amplitude of stimulation was individually adjusted to get effective contractions at acceptable levels of sensation.

Data were collected with Biopack Data Aquisition system. Desriptive statistics and nonparametric statistic tests were used for data evaluation.

III. RESULTS

Mean values of tidal volume, total ventilation and breathing rate during quiet breathing, different stimulus duration and muscle groups stimulated in normal subjects and SCI patients are shown in the Table 1 and Table 2.

Table 1. Values of tidal volume, breathing rate and total ventilation during FES of different muscle groups and duration of stimulus in normal subjects

Muscle group stimulated	Dur. of stimulus (s)	Tidal volume (l)	Breathing rate (br./min)	Ventilation (l/min)
rectus muscles	q. br.	0.680 ± 0.151	13.3 ± 2.9	8.9 ± 2.3
	1	0.995 ± 0.182	15.2 ± 4.4	15.1 ± 4.8
	1.5	1.090 ± 0.246	14.6 ± 2.5	15.9 ± 4.3
	2	1.226 ± 0.305	13.6 ± 1.1	16.4 ± 2.7
lateral group m.	q. br.	0.679 ± 0.135	13.8 ± 2.4	9.3 ± 2.1
	1	1.062 ± 0.257	16.3 ± 2.4	17.3 ± 4.7
	1.5	1.064 ± 0.232	13.9 ± 2.4	15.0 ± 4.4
	2	1.143 ± 0.238	14.1 ± 1.0	16.1 ± 2.6
rectus muscles + lateral group m.	q. br.	0.632 ± 0.120	14.3 ± 1.6	9.1 ± 2.1
	1	1.035 ± 0.292	16.3 ± 1.3	17.1 ± 5.7
	1.5	1.079 ± 0.295	15.9 ± 1.6	17.0 ± 4.1
	2	1.187 ± 0.338	13.5 ± 1.2	15.9 ± 4.0

Table 2. Values of tidal volume, breathing rate and total ventilation during FES of different muscle groups and duration of stimulus in SCI patients

Muscle group stimulated	Dur. of stimulus (s)	Tidal volume (l)	Breathing rate (br./min)	Ventilation (l/min)
rectus muscles	q. br.	1.010 ± 0.151	18.8 ± 2.1	18.7 ± 1.9
	1	1.170 ± 0.171	18.7 ± 4.9	21.1 ± 2.5
	1.5	1.279 ± 0.063	20.7 ± 0.3	26.4 ± 0.9
	2	1.394 ± 0.182	17.4 ± 0.1	24.2 ± 3.3
lateral group m.	q. br.	1.118 ± 0.267	18.2 ± 2.1	19.7 ± 2.6
	1	1.180 ± 0.072	23.7 ± 1.3	27.9 ± 0.1
	1.5	1.303 ± 0.217	23.0 ± 0.5	29.9 ± 4.3
	2	1.299 ± 0.08	19.5 ± 0.1	25.3 ± 1.7
rectus muscles + lateral group m.	q. br.	1.085 ± 0.231	18.8 ± 2.6	19.9 ± 2.2
	1	1.115 ± 0.019	26.5 ± 2.2	29.5 ± 1.9
	1.5	1.433 ± 0.217	22 ± 0.1	31.5 ± 4.9
	2	1.281 ± 0.138	22.0 ± 1.9	27.9 ± 0.5

In normal subjects V_T was significantly increased with prolongation of duration of FES compared to quiet breathing, whereas the breathing rate after the initial increase during 1 second stimulation, showed the decline proportionally to the prolongation of FES. Consequently, total ventilation was increased compared to quiet breathing to the same value, independent of FES combinations applied. From the measured data it is evident that there is no significant differences in ventilation due to different muscle groups stimulated at the same parameters of stimulation. In SCI patients the effects of FES have the same trends as in normal subjects, but have less stable responses to FES. The greater variability of ventilation during different muscles stimulated in SCI subjects were probably due to the spastic episodes during stimulation. Spastic episodes were not equally frequent during measurement periods.

IV. DISCUSSION

The patients who need ventilatory support are usually the candidates for artificial ventilation, usually mechanical one, which is invasive procedure and needs very sophisticated device. The decision when to begin with this lifesaving procedure is often difficult. In transient period different kinds of noninvasive ventilatory support are used. One of new promising non-invasive ventilation support is also FES of abdominal muscles during expiration, where the following mechanism is exploited. In normal subjects, during quiet breathing, inspiration begins from the level of FRC with active lowering of pleural pressure, what is achieved by contraction of diaphragm with consequent flow of the air into the lungs. Expiration phase is realized passively due to elastic recoil of the lungs and returns to the level of FRC, without any significant muscle activity. By FES activated contractions of abdominal muscles during expiration, additional volume is expelled, and the level of end-inspiration is shifted below FRC. The beginning of the next respiratory cycle is then passive to the level of FRC, followed by the next active inspiration phase. In this way the FES of abdominal muscles generates inspiratory support function.

All experiments were done for a short FES duration of 1 minute. For clinical application, it is expected that duration of FES supported ventilation should be in order of several hours. Muscular fatigue is a potential problem in all applications of neuromuscular stimulation and judicious selection of stimulation parameters, particularly stimulation frequency and duty cycle, can reduce and in some case eliminate the fatigue problem, but can be reduced by intermittent mode of stimulation.

With the prolongation of FES increases V_T, but increase is not linear with prolongation, because we reach flow limitation. With adjusted prolongation of stimulation one can achieve maximal value with minimal parameters of stimulation. In normal subjects the optimal parameters of stimulation are 1sec. duty cycle and one group of muscles stimulated. In SCI patients the same parameters of FES supported ventilation can be used initially during

management, but can be adjusted to maintain the stable ventilatory support.

V. CONCLUSIONS

1. FES significantly increases tidal volume and total ventilation in normal subjects and SCI patients
2. prolongation of stimulus increases V_T and decreases breathing rate, total ventilation being changed
3. rectus abdominis muscle with duration of stimulation sequence of one second would be the best solution to begin FES supported ventilation
4. later individually adjustment of time, mode (possibly intermittent) and muscles to be stimulated to get stable ventilatory support
5. further investigation has to be performed to take these conclusions as clinically applicable.

VI. REFERENCES

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